Journal of Forensic and Legal Medicine 20 (2013) 1041–1047

Contents lists available at ScienceDirect

Journal of Forensic and Legal Medicine

journal homepage: www.elsevier.com/locate/jflm

Original communication

# Estimation of sex from the upper limb measurements of Sudanese adults

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A R T I C L E I N F O

*Article history:*
Received 22 April 2013
Received in revised form
26 August 2013
Accepted 29 September 2013
Available online 9 October 2013

*Keywords:*
Forensic anthropology
Identification
Anthropometry
Sex estimation
Upper limb
Sudanese population

A B S T R A C T

Sex estimation is the first biological attribute needed for personal identification from mutilated and amputated limbs or body parts in medical-legal autopsies. Populations have different sizes and proportions that affect the anthropometric assessment of sex. Relatively few published works assess the accuracy of sex estimation from soft tissue measurements of upper limb parts, except for the hand and its components, but these studies involve a limited range of global populations. The current study aimed to assess the degree of sexual dimorphism in upper limb measurements and the accuracy of using these measurements for sex estimation in a contemporary adult Sudanese population. The upper arm length, ulnar length, wrist breadth, hand length, and hand breadth of 240 right-handed Sudanese subjects (120 males and 120 females) aged between 25 and 30 years were measured by international anthropometric standards. Demarking points, sexual dimorphism indices and discriminant functions were developed from 200 subjects (100 males and 100 females) who composed the study group. All variables were sexually dimorphic. The ulnar length, wrist breadth and hand breadth significantly contributed to sex estimation. Forearm dimensions showed a higher accuracy for sex estimation than hand dimensions. Cross-validated sex classification accuracy ranged between 78.5% and 89.5%. The reliability of these standards was assessed in a test sample of 20 males and 20 females, and the results showed accuracy between 77.5% and 90%. This study provides new forensic standards for sex estimation from upper limb measurements of Sudanese adults.



## 1. Introduction

Sex estimation, which is the first biological attribute needed in the identification process of unknown human remains, is essential for constructive profiling. Sex estimation roughly halves the pool of possible victim matches and enables the application of the most appropriate standard to estimate other sex-dependent individual attributes, e.g., age and stature.[1,2] Sex can be estimated with morphological and metric techniques applied to the human skeleton.[1] While it is widely understood that traditionally the skull and pelvis have been considered most reliable for sex determination,[1] many recent articles (e.g., Barrier and L'Abbe,[3] Papaioannou et al.,[4] Srivastava et al.,[5] and Salus et al.[6]) have examined post-cranial skeletal accuracy and reliability in sex determination.[1] The increased likelihood of pelvic and skull absence when body integrity is compromised, such as during mass disasters, wars, traffic accidents, and assault cases, and the likelihood of recovering separated limbs necessitate the determination of the primary indicators of identification from limb parts.[5,7] In addition, comparison of skull and postcrania sex discrimination has shown that the postcrania metrics provide better estimates of sex than non-metric and metric traits of the skull.[5,8]

Anthropometry is the science of measurements of the size, weight and proportions of the human body and skeleton.[9] Anthropometry is considered to be a multifaceted technique to investigate sexual dimorphism; anthropometry has high precision and validity and is practical and quantifiable by discriminant and regression analyses.[3,10] Additionally, anthropometry provides sex estimation standards from contemporary living populations and overcomes some limitations inherent in osteometric skeletal collections, e.g., wrong recording, dynamicity of the population, and lack of collections in some countries.

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http://dx.doi.org/10.1016/j.jflm.2013.09.031

A number of studies have addressed the issue of sex determination based on osteologic and radiologic examination of upper limb bones.[3,4,11–16] However, an extensive literature review revealed a relative scarcity of published research assessing the accuracy of sex estimation from soft tissue measurements of most of upper limb parts; furthermore, the most studied part is the hand and its parts, but these studies involve a limited range of global populations, e.g., India, Turkey, Egypt, and West Australia. Therefore, sex estimation from soft tissue measurements remains a relatively novel approach in forensic anthropology.[17] Kanchan and Rastogi[18] studied hands dimensions, as well as hand and palm indices, among North and South Indian population to assess sexual dimorphism, and they reported that hand dimensions are better discriminators than indices and concluded that hand breadth is the most sexually dimorphic dimension. Similar findings were found in the Rajput population from northern India.[19] The sex identification prospective of hand length and breadth were explored in Indo-Mauritian population and reliability was proved.[20] Ishak et al.,[17] evaluated the accuracy of using anthropometric hand measurements for sex estimation in a contemporary adult Western Australian population, and they found that hand breadth and length are the most significant contributors to sex discrimination.

Few published studies report on sex estimation using other parts of live upper limbs, except for the hand and its parts.[21,22] Aye[23] assessed the usefulness of arm bone dimensions in sex assignment. He measured the wrist circumference, arm span and arm length, derived a discriminant stepwise function using the wrist and arm span and obtained average accuracy between 81.1 and 89%. According to sources cited by Holman and Bennett,[24] the wrist breadth was the most sexually dimorphic trait among living Eskimos, as well as unlike-sex dizygotic twins and unrelated adults from New York City.

The geographical localization of Sudan in northeastern Africa and the presence of the Nile has enhanced migrations of Arabs, Turks, and Copts to Sudan. These migrations resulted in a unique admixture of Arabs and local African populations, e.g., Nubians, in the majority of contemporary Sudan inhabitants. In response to the glaring shortage of Sudanese identification system standards due to the lack of records such as fingerprints, antemortem dental records and the high cost of DNA analysis, Sudanese limbs were explored to assess the possibility of use for stature and sex estimation. Reports indicate sexual dimorphism among Sudanese limbs and argue that limbs can be used for stature and sex estimation.[25–27] There currently are no population-specific standards for sex estimation from Sudanese upper limb measurements in spite of the escalating excessive violent crimes, civil war and tribal conflicts, and difference in the skeletal biology and body proportions of Sudanese compared with other populations, even the Egyptians and others in close proximity.[25,27] Hence, the aims of this study are to explore sexual dimorphism of Sudanese upper limb measurements and provide population specific standards and posterior probabilities for sex assignment of unknown subjects based on these measurements. These standards would provide a sex estimation method for forensic investigators confronted with disarticulated or incomplete human upper limb parts. In addition, this research will provide valuable data for further comparison with other Arab people living in Sub-Saharan regions or individuals with a mixed genetic background including African descent in the Arabian Peninsula.

## 2. Materials and methods

### 2.1. Sample

A total of 240 normal, healthy Sudanese Arab volunteers, 120 males and 120 females, were recruited in the Khartoum teaching hospital over four weeks. Subjects were required to sign a consent form and complete a questionnaire with basic demographic data and general questions, e.g., handedness. The subjects were between 25 and 30 years of age; the mean age for males was 27.8 $\pm$ 1.3 and females was 27.6 $\pm$ 1.4, and all subjects were right-handed. No subjects had a history of chronic illness, trauma, physical deformity, or any surgical procedure that might affect upper limb dimensions. The study received approval from the ethical committee of the Faculty of Medicine, University of Khartoum.

### 2.2. Measurements

Using standard anthropometric instruments, five upper limb dimensions of each subject were measured in centimeters to the nearest millimeter. The existence of a significant directional asymmetry in upper limb dimensions associated with dominance, has been suggested in various studies.[28,29] Therefore, all upper limb measurements were taken on the left side.[30,31] Necessary precautions were taken while measuring the subjects. The instruments were checked regularly for accurate readings. All measurements were obtained in a well-lit room and repeated in triplicate, and the means of the measurements were recorded. These measurements included the parameters detailed in the following sections.

#### 2.2.1. Upper arm length

Upper arm length was measured with a Harpenden anthropometer (Holtain Ltd, Crosswell, UK) and considered to be the distance between the marked inferior border of the acromion process to the external superior border of the head of the radius.[30]

#### 2.2.2. Ulnar length

The subjects were asked to flex their elbow to 90° and extend their fingers in the direction of the long axis of the forearm. Then, ulnar length was measured with a Harpenden anthropometer as the direct distance between the most proximal point of the olecranon process and the styloid process.[32]

#### 2.2.3. Wrist breadth

Wrist breadth was taken with a digital sliding caliper (Mitutoyo, Japan) as the distance between the ulnar and radial styloid processes.[30]

#### 2.2.4. Hand length

The subjects were instructed to sit and place their left hand on a flat, hard horizontal surface with the thumb abducted and the other four extended and adducted. Then, hand length was taken with a digital sliding caliper as the straight distance between the midpoints of the distal crease of the wrist to the most anterior projection of the skin on the middle finger.[33]

#### 2.2.5. Hand breadth

Hand breadth was taken with a digital sliding caliper as the distance between the most lateral point on the head of the second metacarpal bone and the most medial point on the head of the fifth metacarpal bone.[34]

### 2.3. Statistical analysis

The data were randomly split into two categories: 200 Subjects (100 male, 100 female) were used as the study group, and 40 subjects (20 male, 20 female) were used as test group validation. The statistical analysis was performed with the Statistical Package for the Social Sciences (SPSS), version 14 (SPSS Inc., Chicago, IL). A study to assess the precision and reliability of acquiring upper limb measurements was conducted prior to primary data collection. The

upper limb dimensions of ten subjects were measured on three different evaluation days, with two days between re-measurements. Then, the intra-observer measurement error and reliability were calculated to be within the acceptable standards for all measurements ($r > 0.9$; $r$ TEM $< 5\%$).[35] Initially, descriptive statistics (means, standard deviations and ranges) were generated to summarize anthropometric measurements. The presence of statistically significant sexual dimorphism between males and females was assessed with an independent $t$-test. A $p$-value of $<0.05$ was considered to be significant. Sex differentiation from upper limb dimensions was analyzed with discriminant analysis (direct, stepwise and multiple), from which equations for assigning sex were created.

Each of the five measurements was individually subjected to direct discriminant analysis to test its efficacy in sex determination. Then, discriminant function analyses (stepwise and multiple) used the five measurements as independent variables. Keeping in mind the possibility of finding a dismembered upper limb, three measurements of upper limbs, excluding the hand, and two hand measurements were used to identify the quantitative measurement functions that can discriminate between sexes. The average of the function centroids within each discriminant formula created a sectioning point between males and females. Using this discriminant equation, any values calculated equal to or greater than zero were classified as male, and values less than zero were classified as female. To analyze the effectiveness of these functions in sex assignment, a cross-validation method "leave-one-out classification" technique was applied to the sample to measure the accuracy rate of the original sample and the cross-validation sample. More accurate results obtained in the cross-validation sample indicate a greater reliability of the discriminant function. In addition, the posterior probabilities of correct group membership were calculated to measure the effectiveness of each discriminant function and measure the strength of a correct classification, where values are larger with increasing distance from the sectioning point. The data were additionally analyzed using a cut off value for sex determination "demarking point", which was calculated by taking the average of the male and female means. Scores greater than the demarking point were classified as male sex and scores less than the demarking point were classified as female. The demarking points and discriminant equations were tested, and the accuracy between the study and test samples was compared.

## 3. Results

Descriptive statistics for upper arm length, ulnar breadth, wrist breadth, hand length, and hand breadth for both sexes are presented in Table 1. It is apparent that male values are higher than female values for all dimensions. When the equality of the means of males and females are compared with the $t$-test, all measurements were significantly larger for males than females ($P$-value $< 0.001$). These results indicate the existence of sexual dimorphism in the sample under study. The $t$-test values indicate that the ulnar length is the most sexually dimorphic measurement, followed by hand breadth, hand length and wrist breadth, while the upper arm length is less dimorphic. The sexual dimorphism index for the five measurements was calculated by dividing the male mean by the female mean for the same measurement and multiplied by 100; indices higher than 100 indicate better sex estimation. The indices in this study were 109.85, 112.54, 112.78, 111.32, and 112.09 for upper arm length, ulnar breadth, wrist breadth, hand length, and hand breadth, respectively.

A direct univariate discriminant function analysis and demarking points were created for the five measurements (Table 2). Classification accuracy ranged between 78.5% and 88.5% in the study group and 77.5%–90% in the test groups (see Table 5); the most dimorphic individual measurements show the highest accuracy, indicating that the ulnar length was the most sexually dimorphic (88.5% in the study group and 90% in the test group) followed by hand breadth (85.5% in the study group and 82.5% in the test group), and the least sexually dimorphic was the upper arm length (78.5% in study group and 77.5% in the test group).

Table 3 presents the stepwise analyses used to determine which of the five measurements most affect the functions. When an entire upper limb was present, three variables were selected: ulnar length, wrist breadth, and hand breadth, with expected classification accuracy of 89.5% for the study group and 87.5% for the test group (Table 5). Assuming that the upper limb may be found without the hand, another stepwise analysis was used to determine which of the three measurements have the most impact; the ulnar length and the wrist breadth were the two variables selected, with an expected classification accuracy of 89% for the study group and 90% for the test group (Table 5).

The multiple direct discriminant analyses are presented in Table 4. Notably, the overall accuracy rate calculated by the direct discriminant function for the hand using hand length and breadth was closer to the accuracy rate obtained by the hand breadth alone in the study group (85% for both and 85.5% for breadth alone). However, there was increasing accuracy in the testing group (82.5% for hand breadth and 87.5% for both hand dimensions), and using the five measurements together generated similar results to using stepwise or forearm alone (Table 5).

Table 6 presents the percentages of posterior probability intervals of correct sex classification for functions 1–7. It is evident that between 66.7% and 95.5% of male and female individuals were classified above 80% certainty for functions 2–7. Lower posterior probability values were evident for function 1, but the majority of individuals in both sexes were classified above 60% certainty. There were no correctly classified individuals with a posterior probability less than 40%.

## 4. Discussion

Recent research has focused on upper limb anthropometric measurements, especially the hand and its parts, due to the relative paucity of literature regarding its use in sex estimation.[17–20,23] The

**Table 1**
Descriptive statistics for upper limb measurements (in cm) in both sexes.

| Parameter | Males | | | | Females | | | | Independent $t$-test | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Min | Max | Mean | SD | Min | Max | $t$-Value | $P$ (2-tailed) |
| Upper arm length | 31.68 | 1.76 | 28.30 | 36.90 | 28.84 | 1.65 | 24.30 | 33.00 | 11.760 | 0.000[a] |
| Ulnar length | 29.25 | 1.52 | 25.70 | 34.30 | 25.99 | 1.46 | 22.40 | 29.70 | 15.456 | 0.000[a] |
| Wrist breadth | 5.56 | 0.34 | 4.84 | 6.30 | 4.93 | 0.34 | 4.30 | 5.90 | 13.082 | 0.000[a] |
| Hand length | 19.17 | 1.14 | 16.80 | 21.80 | 17.22 | 0.88 | 14.90 | 19.10 | 13.202 | 0.000[a] |
| Hand breadth | 7.88 | 0.55 | 6.50 | 8.90 | 7.03 | 0.35 | 6.30 | 8.00 | 13.368 | 0.000[a] |

SD: Standard Deviation.
[a] The $t$-test was significant at the 0.001 level (2-tailed).

**Table 2**
Univariate discriminant function equations of upper limb measurements and demarking points (in cm) for sex estimation.

| Function | Variables | Unstandardized coefficient | Constant | Wilk's lambda | Group centroids | Demarking points |
|---|---|---|---|---|---|---|
| 1 | UAL | 0.586 | −17.739 | 0.589 | M = 0.832, F = −0.832 | F < 30.26 < M |
| 2 | UL | 0.670 | −18.509 | 0.453 | M = 1.093, F = −1.093 | F < 27.62 < M |
| 3 | WB | 2.940 | −15.429 | 0.536 | M = 0.925, F = −0.925 | F < 5.24 < M |
| 4 | HL | 0.985 | −17.930 | 0.517 | M = 0.942, F = −0.942 | F < 18.20 < M |
| 5 | HB | 2.184 | −16.281 | 0.537 | M = 0.964, F = −0.964 | F < 7.45 < M |

UAL = upper arm length, UL = ulnar length, WB = wrist breadth, HL = hand length, HB = hand breadth, M = males, F = females.

**Table 3**
Discriminant function analysis (Stepwise) of upper limb measurements.

| Function | Variables | Unstandardized coefficient | Standardized coefficient | Wilk's lambda | Structure point | Group centroids |
|---|---|---|---|---|---|---|
| Function 6: upper limb | | | | | | |
| 1 | UL | 0.404 | 0.604 | 0.453 | 0.838 | M = 1.305 |
| 2 | WB | 1.267 | 0.431 | 0.380 | 0.709 | F = −1.305 |
| 3 | HB | 0.583 | 0.267 | 0.368 | 0.708 | |
| | Constant | −22.164 | | | | |
| Function 7: upper limb excluding hand | | | | | | |
| 1 | UL | 0.478 | 0.713 | 0.453 | 0.860 | M = 1.271 |
| 2 | WB | 1.562 | 0.531 | 0.380 | 0.728 | F = −1.271 |
| | Constant | −21.402 | | | | |

UL = ulnar length, WB = wrist breadth, HB = hand breadth, M = males, F = females.

results of this study indicate a significant degree of sexual dimorphism in the upper limbs among the Sudanese population. Hence, the discriminant equations developed in the present study will be of important utility for forensic investigators.

The present study results showed that the means of the five upper limb measurements used were different from other populations, indicating body physique differences attributable to such factors as genetic background, nutrition, climate, and physical activity levels.[33,36] The five measurements used expressed statistically significant sexual dimorphism ($p < 0.001$). These findings are in accordance with previous studies that used anthropometric measurements in various populations, e.g., Nigerians,[23,37] Indians,[18,19] Egyptians,[38] Turkish,[39] and West Australians.[17] To the best of my knowledge, there is no published literature on sex estimation from anthropometric measurements of the upper arm length, ulnar length, and wrist breadth in living subjects. Therefore, some findings of this study were compared with previous published studies that used direct measurements of bone dimension or mimicked dimensions. The ulnar length was found to be the most sexually dimorphic variable in Sudanese upper limbs, followed by the wrist breadth and hand breadth, while the upper arm length showed the least sexual dimorphism. The sexual dimorphism indices are used as comparative tools between this population and other published studies (Table 7). The sexual dimorphism index of the upper arm length was 109.85, which was close to black American[24] and Cretan[40] populations, lower than Greek,[41] black South African,[42] and Chinese[43] populations, and higher than white American,[24] German,[36] white South African,[42] Iranian,[44] Japanese,[43] and Thai[43] populations. The ulnar length index was 112.54, which was close to Greeks,[41] but higher than Americans,[24] Germans,[36] black South Africans,[3] and Turks.[12,39] To compare the wrist index obtained in this study with other published studies, bones were mimicked by combining the mean values of the radius and ulna distal breadths as suggested by Holman and Bennett.[24] The wrist breadth index among the Sudanese was 112.78, which was close to the Turkish population[12] and lower than German[36] and American[24] populations. The hand length demonstrated an index of 111.32, which was close to the Indian population[18] and the right hand index among the west Australian[17] population, but higher than the Nigerian,[37] Egyptian,[38] Iranian,[44] and Rajputs Indian[19] populations. The hand breadth index was 112.09, close to Iranian[44] and Nigerian[37] populations, lower than Egyptian,[38] South Indian,[18] and right hand indices among west Australian[17] populations, and higher than North and Rajput Indian populations.[18,19] The data confirm that different body parts express different sexual dimorphism patterns between populations and within the same

**Table 4**
Direct discriminant function equations of upper limb measurements.

| | Variables | Unstandardized coefficient | Standardized coefficient | Wilk's lambda | Structure point | Group centroids |
|---|---|---|---|---|---|---|
| Function 8 | UAL | 0.010 | 0.016 | 0.380 | 0.654 | $M = 1.271$ |
| | UL | 0.470 | 0.701 | | 0.860 | $F = -1.271$ |
| | WB | 1.561 | 0.531 | | 0.728 | |
| | Constant | −21.463 | | | | |
| Function 9 | HL | 0.597 | 0.606 | 0.465 | 0.902 | $M = 1.067$ |
| | HB | 1.145 | 0.524 | | 0.866 | $F = -1.067$ |
| | Constant | −19.390 | | | | |
| Function 10 | UAL | 0.019 | 0.032 | 0.367 | 0.637 | $M = 1.305$ |
| | UL | 0.375 | 0.560 | | 0.837 | $F = -1.305$ |
| | WB | 1.258 | 0.428 | | 0.709 | |
| | HL | 0.033 | 0.034 | | 0.737 | |
| | HB | 0.563 | 0.258 | | 0.708 | |
| | Constant | −22.343 | | | | |

UAL = upper arm length, UL = ulnar length, WB = wrist breadth, HL = hand length, HB = hand breadth, M = males, F = females.

**Table 5**
Demarking points (in cm) for sex estimation and classification accuracy expressed as percentages.

| Variable | Demarking points | Predicted group | Expected accuracy study group | | | Expected accuracy test group | | |
|---|---|---|---|---|---|---|---|---|
| | | | Total | Males | Females | Total | Males | Females |
| F1 UAL | 30.26 | Original | 78.5% | 77% | 80% | 77.5% | 80% | 75% |
| | | Cross- validated | 78.5% | 77% | 80% | | | |
| F2 UL | 27.62 | Original | 88.5% | 89% | 88% | 90.0% | 90% | 90% |
| | | Cross- validated | 88.5% | 89% | 88% | | | |
| F3 WB | 5.24 | Original | 83.5% | 83% | 84% | 87.5% | 95% | 80% |
| | | Cross- validated | 83.5% | 83% | 84% | | | |
| F4 HL | 18.20 | Original | 80.5% | 78% | 83% | 87.5% | 85% | 90% |
| | | Cross- validated | 80.5% | 78% | 83% | | | |
| F5 HB | 7.46 | Original | 85.5% | 78% | 93% | 82.5% | 85% | 80% |
| | | Cross- validated | 85.5% | 78% | 93% | | | |
| F6 (stepwise) | | Original | 90.5% | 88% | 93% | 87.5% | 90% | 85% |
| | | Cross- validated | 89.5% | 88% | 91% | | | |
| F7 UL + WB | | Original | 89.0% | 87% | 91% | 90.0% | 95% | 85% |
| | | Cross- validated | 89.0% | 87% | 91% | | | |
| F8 UAL + UL + WB | | Original | 89.5% | 87% | 92% | 90.0% | 95% | 85% |
| | | Cross- validated | 88.0% | 87% | 89% | | | |
| F9 HL + HB | | Original | 85.0% | 79% | 91% | 87.5% | 95% | 80% |
| | | Cross- validated | 85.0% | 79% | 91% | | | |
| F10 All | | Original | 91.0% | 89% | 93% | 87.5% | 90% | 85% |
| | | Cross- validated | 88.5% | 88% | 89% | | | |

UAL = upper arm length, UL = ulnar length, WB = wrist breadth, HL = hand length, HB = hand breadth.

**Table 6**
Percentage of posterior probability intervals of the correct classification of sex for upper limb.

| Posterior probability intervals | Males | | Females | |
|---|---|---|---|---|
| | *N* | % | *N* | % |
| **Function 1: UAL** | | | | |
| 0.40–0.59 | 6 | 7.79 | 11 | 13.75 |
| 0.60–0.79 | 27 | 35.06 | 21 | 26.25 |
| 0.80–1.00 | 44 | 57.14 | 48 | 60.00 |
| **Function 2: UL** | | | | |
| 0.40–0.59 | 3 | 3.37 | 2 | 2.27 |
| 0.60–0.79 | 21 | 23.60 | 18 | 20.45 |
| 0.80–1.00 | 65 | 73.03 | 68 | 77.27 |
| **Function 3: WB** | | | | |
| 0.40–0.59 | 10 | 12.05 | 8 | 9.52 |
| 0.60–0.79 | 17 | 20.48 | 20 | 23.81 |
| 0.80–1.00 | 56 | 67.47 | 56 | 66.67 |
| **Function 4: HL** | | | | |
| 0.40–0.59 | 6 | 7.69 | 2 | 2.41 |
| 0.60–0.79 | 13 | 14.94 | 22 | 26.51 |
| 0.80–1.00 | 59 | 75.64 | 59 | 71.08 |
| **Function 5: HB** | | | | |
| 0.40–0.59 | 6 | 7.69 | 8 | 8.60 |
| 0.60–0.79 | 12 | 15.38 | 16 | 17.20 |
| 0.80–1.00 | 60 | 76.92 | 69 | 74.19 |
| **Function 6** | | | | |
| 0.40–0.59 | 6 | 6.82 | 2 | 2.20 |
| 0.60–0.79 | 8 | 9.09 | 4 | 4.40 |
| 0.80–1.00 | 74 | 84.09 | 85 | 93.41 |
| **Function 7** | | | | |
| 0.40–0.59 | 2 | 2.30 | 4 | 4.40 |
| 0.60–0.79 | 12 | 13.79 | 6 | 6.59 |
| 0.80–1.00 | 73 | 83.91 | 81 | 89.01 |
| **Function 8** | | | | |
| 0.40–0.59 | 2 | 2.30 | 2 | 2.25 |
| 0.60–0.79 | 11 | 12.64 | 6 | 6.74 |
| 0.80–1.00 | 74 | 85.06 | 81 | 91.01 |
| **Function 9** | | | | |
| 0.40–0.59 | 4 | 5.06 | 5 | 5.49 |
| 0.60–0.79 | 7 | 8.86 | 13 | 14.29 |
| 0.80–1.00 | 68 | 86.08 | 73 | 80.21 |
| **Function 10: All variables** | | | | |
| 0.40–0.59 | 8 | 9.09 | 0 | 0 |
| 0.60–0.79 | 8 | 9.09 | 4 | 4.49 |
| 0.80–1.00 | 72 | 81.82 | 85 | 95.51 |

UAL = upper arm length, UL = ulnar length, WB = wrist breadth, HL = hand length, HB = hand breadth.

population.[41] In addition, the data show that sexual dimorphism is generally more evident in Sudanese breadth dimensions and ulnar length. Findings indicate that bone lengths are primarily affected by genetics, and a strong association has been reported between genes and tibia and femur lengths.[45,46] Distinct ethnic axial and appendicular growth patterns have been observed in different communities and socioeconomic statuses, indicating that genetic factors are the primary impact relative to other environmental factors.[47,48]

**Table 7**
Comparison of the present study with previously published findings on the upper limb measurements using sexual dimorphism indices.

| Study | Place and method | UAL | UL | WB | HL | HB |
|---|---|---|---|---|---|---|
| | | SDI | SDI | SDI | SDI | SDI |
| The present study | Sudan[L] | 109.85 | 112.54 | 112.78 | 111.32 | 112.09 |
| Aboul-Hagag et al.[38] | Eygpt[L] | | | | 107.32 | 113.52 |
| Danborno and Elukpo[37] | Nigeria[L] | | | | 107.61 | 112.44 |
| Holman and Bennet[24] | United States (Black)[S] | 109.53 | 110.81 | 115.67 | | |
| Steyn and Iscan[42] | South Africa (Black)[S] | 111.30 | | | | |
| Barrier and L'Abbe[3] | South Africa (Black)[S] | | 109.84 | | | |
| Charisi et al.[41] | Greek[S] | 110.27 | 112.33 | 116.00 | | |
| Mall et al.[36] | German[S] | 108.79 | 111.34 | | | |
| Kranoti and Michalodimitrakis[40] | Cretan[S] | 109.50 | | | | |
| Celbis and Agritmis[39] | Turkey[F] | | 111.86 | | | |
| Uzun et al.[12] | Turkey[S] | | 110.65 | 113.10 | | |
| Holman and Bennet[24] | United States (White)[S] | 108.01 | 110.13 | 115.47 | | |
| Steyn and Iscan[42] | South Africa (White)[S] | 108.27 | | | | |
| Ishak et al.[17] | Australia[L] | | | | 111.09 | 114.75 |
| Akhlaghi et al.[44] | Iran[L] | 108.06 | | | 110.38 | 112.48 |
| Krishan et al.[19] | North India[L] | | | | 108.59 | 111.23 |
| Kanchan and Rastogi[18] | North India[L] | | | | 111.17 | 111.27 |
| Kanchan and Rastogi[18] | South India[L] | | | | 111.17 | 112.68 |
| Iscan et al.[43] | Chinese[S] | 110.61 | | | | |
| Iscan et al.[43] | Japanese[S] | 107.40 | | | | |
| Iscan et al.[43] | Thai[S] | 107.78 | | | | |

UAL = upper arm length, UL = ulnar length, WB = wrist breadth, HL = hand length, HB = hand breadth, SDI = sexual dimorphism index.
L = Living.
F = Fresh cadaver.
S = Skeleton.

Reports indicate that blacks have longer ulnas, radii, and tibiae than whites, while whites have longer humeri than blacks for both sexes.[49] The other factor found to affect long bones lengths is nutritional status; bone lengths changed positively in association with improvements in health and nutrition, which are more common in males than females.[49] Case and Ross[15] indicated relatively small magnitudes in epiphyseal end changes following functional loading when compared with overall length. In contrast, high sexual dimorphism in wrist and hand breadth may indicate different body frames, muscular activity, and a higher growth rate of the male cortical bones compared to their females counterparts.[50] Therefore, the findings of this study can be attributed primarily to the genetic factor, and secondarily to functional constraints and environmental factors, such as diet, health and physical activity, which result in musculature differences between sexes.[1,41,47]

The expected accuracy of the ulna to classify sex was found to be 88.5% (89% males and 88% females) for the study group and 90% for the test group (90% each), which was higher than the expected accuracy for the upper arm length (78.5% for study group and 77.5% for test group). These results concur with the findings of previous studies of long bones of the arm in several populations, which showed that ulna length is a good sex discriminator. The ulnar length was found to correctly assign sex in 91.3% of Turkish corpses (88.8% of males and 95.7% of females)[39]; furthermore, the ulnar length showed better sex discrimination than the humeral length in a Japanese population (83% for ulnar length and 70% 70% for humeral length)[51] and a German population (87.05% for ulnar length and 80.58% for humeral length.[36] However, this finding disagrees with reported results among blacks in the Terry collection, where the ulnar length used in equations to estimate sex resulted in reduced accuracy, leading to Holman and Bennett's[24] suggestion that ulnar length should be used with caution. The maximum humerus length could correctly assign sex in 85.10% of the Cretan population (88.10% of males and 82.14% of females). This higher accuracy for the ulnar length compared to the upper arm length among Sudanese can be due to genetic factors because the ulna had shown a strong link with Sudanese stature, which is mainly controlled by genetics.[25] Humphrey[52] indicated that the developmental basis of sexual dimorphism expression in long bones are dependent on energetic and time constraints, which affect growth rate and growth duration, respectively. The proximal epiphysis of the humerus, which is responsible for approximately 80% of growth in length, fuses with the shaft when a female is 13–17 years old or a male is 16–20 years old, while fusion in the distal epiphysis, the growing end of the ulna that is responsible for 75–85% of growth in length, begins at 15–17 years in females and 17–20 years in males.[53] Therefore, these findings among the Sudanese can be explained by the longer growth duration in the genetically prepared long bone.

The wrist breadth in this study could classify sex with 83.5% accuracy (83% for males and 84% for females) in the study group and 95% for males and 80% for females in the test group. This result agrees with research in the American population, which used the semi-bistyloid breadth and showed an expected accuracy of 84% in males and 80% in females in blacks and 92.3% in males and 84.6% in females in whites.[24] A study in Japan used separated distal forearm bones measurements, i.e., distal radius breadth and ulna head transverse diameter, to correctly assign sex with 92% and 83% accuracy, respectively.[51] The distal radial breadth could successfully assign sex with 80% of males and 83% of females in South Africa.[3] In contrast, the distal radial and ulnar breadth found to be less dimorphic among Germans because the accuracy rates were 78.26% and 78.42%, respectively.[36] The results of this study showed that hand breadth correctly assigned sex for 85.5% (78% of males and 93% for females). Therefore, hand breath is more dimorphic than length, which assigned sex in 80.5% (78% of males and 83% of females). This finding is in agreement with the findings of previous studies of Indians and West Australians.[17–19] Jowaheer and Agnihorti[20] reported that hand length and breadth had an expected sex estimation accuracy of 91.2% among the Indo-Mauritian population. The sexual dimorphism in breadth dimensions, which is primarily developmental in nature, has been attributed to muscular activity and hormones that primarily affect the critical growth phase acting upon a predominant and population specific genetic model.[54–56] While epiphyseal plate fusion stops long bone growth at an earlier age, breadth growth continues due to differential cortical remodeling.[57] This remodeling continues throughout life in response to the effect of physical activities related to occupation, nutrition, and lifestyle (in the period of late growth). This situation may result in subsequent dimorphism in width measurements.[5]

The findings of this study showed high sexual bias of >5% when using hand breadth alone or in combination with length, in accordance with the findings of Krishan et al.[19] in Rajput Indians but higher than the findings of Kanchan and Rastogi[18] in North and South Indians and Ishak et al.[17] in west Australians. This difference can be due to less breadth robusticity in some males, leading to their misclassification as females, or the wide spectrum of male size variability, in contrast to the close cluster of females within a small range.[3]

The multiple discriminant functions (direct and stepwise) showed higher accuracy rates compared with the univariate analyses. The direct multiple discriminant functions used five measurements and demonstrated an accuracy rate close to the stepwise approach, which only used ulnar length, wrist breath and hand breadth (88.5%–89.5% in the study group and 87.5%–87.5% in the test group, respectively). Keeping in mind the possibility of only finding a hand, the results for hand length and breadth showed discrimination, with an accuracy rate of 85% for the study group and 87.5% for the test group. These accuracy rates were lower than hand breadth alone, indicating different intra-limb part proportions. Considering the chance of finding the upper limb with an amputated hand, the results of this study showed that the ulnar length and wrist breadth can provide results close to the stepwise findings.

To assess predictive error in the discriminant analyses of the five measurements and avoid over-fitting my data, the resultant functions were cross-validated with a leave-one-out approach. The high posterior probability values obtained in this study provide further confidence in the suggested individual classification assignments as recommended by Steyn and Iscan.[42]

The success of achieving high sex estimation accuracy is primarily based on the degree of sexual dimorphism inherent in the population and completeness of the remains.[1] The sex-specific minimum predictive accuracy of an equation is more important than the highest pooled accuracy.[11] Two points should be considered when choosing a preferred equation. First, consider the stability of the relationship between sex and measurement used in the study sample and test group as expressed in the presence of a relatively high discriminant accuracy in both groups. Second, consider which equation gives both a high pooled accuracy and relatively similar results for both sexes, i.e., low sex biases.[11,17] Hence, the preferred equations for the Sudanese would be using ulnar length for dismembered parts and the stepwise equation for complete upper limbs.

## 5. Conclusion

The recovery of limbs or dismembered parts in medico-legal investigations requires rapid and reliable techniques for personal identification, especially when the utility of DNA analysis is limited by economic issues or other difficulties, such as wars or mass

disasters. The application of demarking points and discriminant functions using simple anthropometric measurements during forensic examination can provide rapid and accurate sex estimation. There is no doubt that different body parts express different sexual dimorphism patterns between populations. In this study, new Sudanese sex estimation forensic standards were outlined using demarking points and discriminant equations derived from Sudanese upper limb measurements. The study successfully reports sexual dimorphism in upper limb dimensions. The ulnar length, wrist breadth, and hand breadth showed better accuracy than the upper arm length and hand length, and the forearm alone was better than the hand alone.

*Ethical approval*

The study received approval from the ethical committee of the Faculty of Medicine, University of Khartoum.

*Funding*

None.

*Conflict of interest*

There were no conflicts of interest with this research or the manuscript.

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